Semileptonic *B* Decays at BaBar

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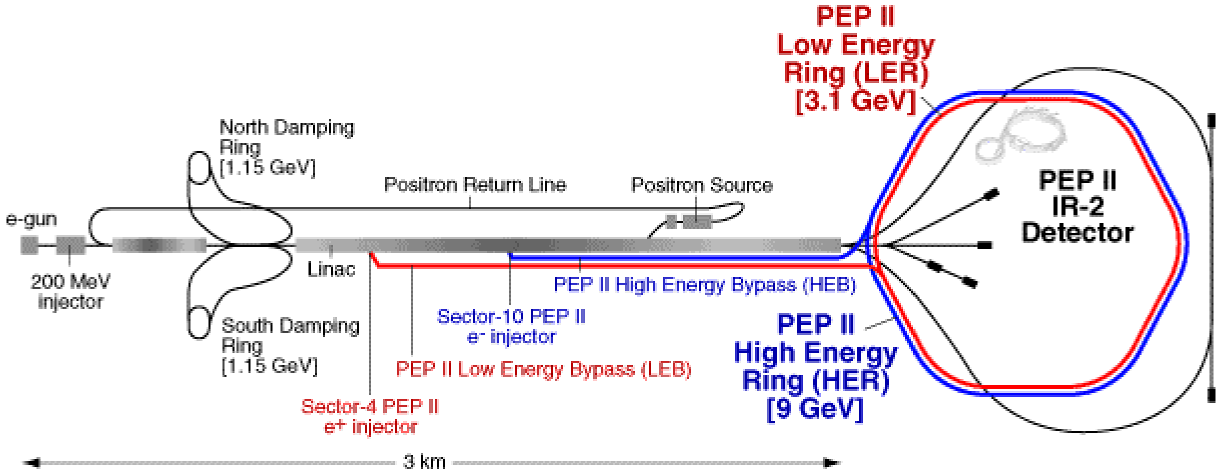
Outline

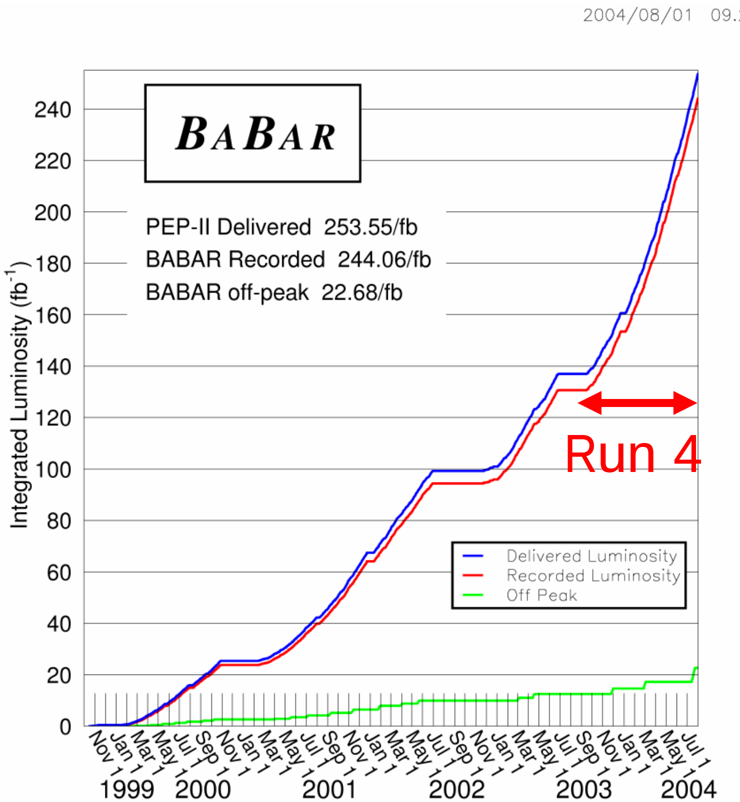
- Introduction
  - PEP-II and BABAR Experiment
  - Why semileptonic B decays?
- Measurements
  - Inclusive $b \to c\ell\nu$ ➔ $|V_{cb}|$, m_b, m_c
  - Inclusive $b \to u\ell\nu$ ➔ $|V_{ub}|$
  - Exclusive $B \to D^*\ell\nu$ ➔ $|V_{cb}|$
  - Exclusive $B \to \pi\ell\nu$ ➔ $|V_{ub}|$
- Summary

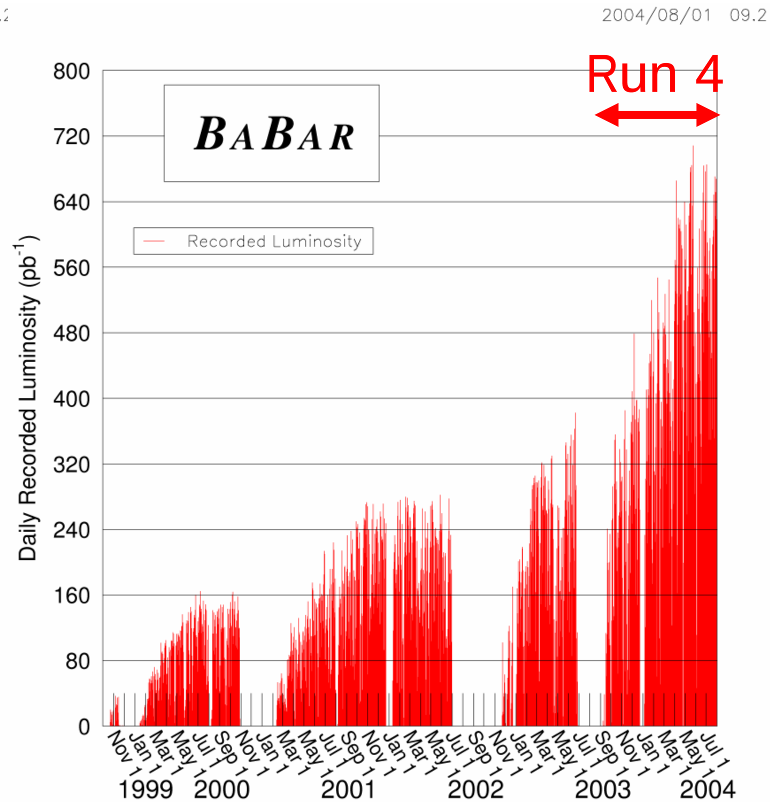
PEP-II Asymmetric B Factory

- Collides 9 GeV e^- against 3.1 GeV e^+
  - E_{CM} = 10.58 GeV = mass of $\Upsilon(4S)$
    - Lightest $b\bar{b}$ resonance that decays into $B\bar{B}$ meson pair
  - Boost $\beta\gamma = 0.56$ allows measurement of B decay times
- Peak luminosity 9.2×10^{33}/cm^2/s ➔ $B\bar{B}$ production ~10 Hz
  - More than 3× the design luminosity!



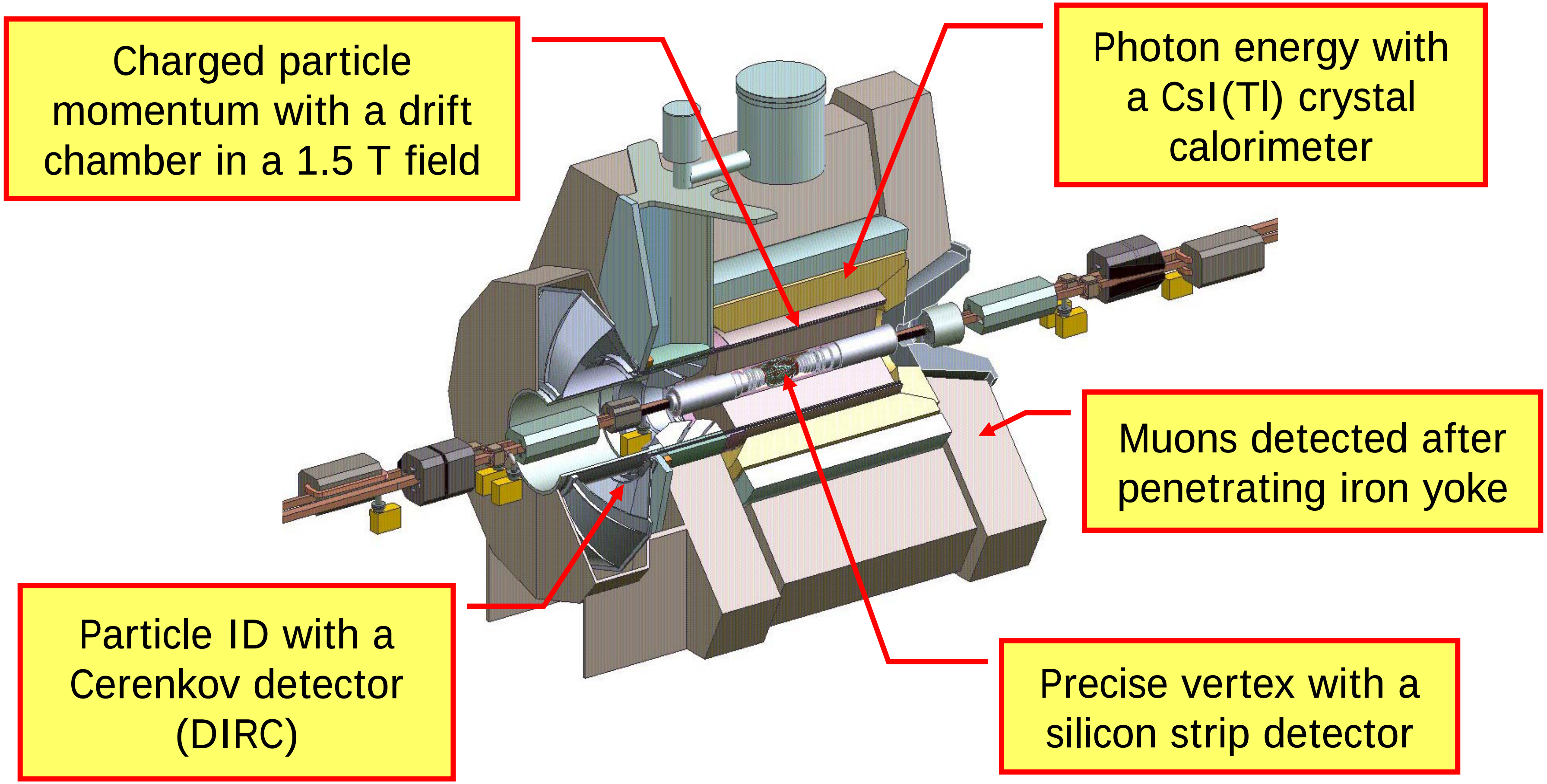
PEP-II Luminosity





- BABAR has accumulated 244 fb^{-1} of data
  - Run 4 (Sep'03-Jul'04) was a phenomenal success

BaBar Detector



B Mesons, CP violation

- *B* Factories produce ~2×10^8 *B* mesons/year
  - B^+ and B^0 are the most accessible 3rd-generation particles
- Their decays allow detailed studies of the CKM matrix

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\begin{pmatrix}\bar{u}_L & \bar{c}_L & \bar{t}_L\end{pmatrix}\gamma^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + h.c.$$

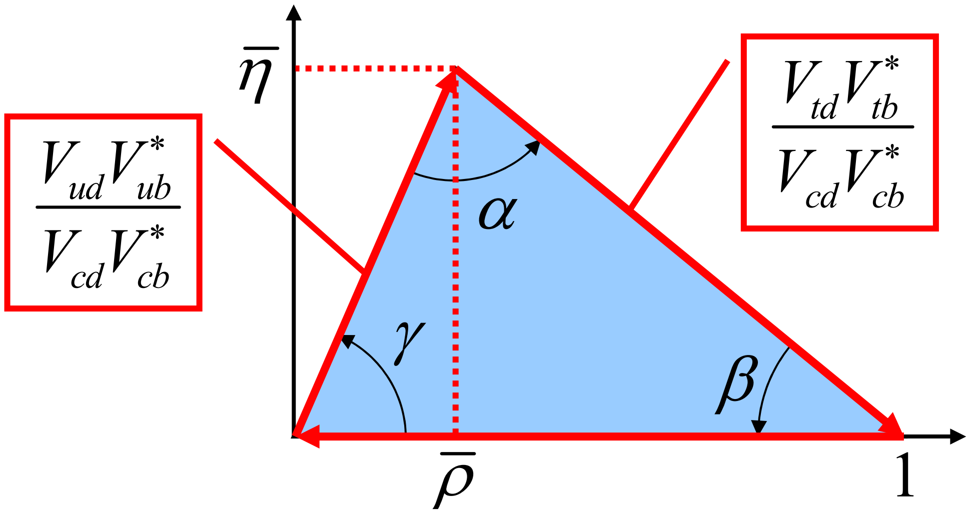
  - Unitary matrix V_{CKM} translates mass and weak basis
  - 3 real parameters + 1 complex phase

The only source of CPV in the Minimal SM

- Is this the complete description of the CP violation?
  - Is everything consistent with a single unitary matrix?

Unitarity Triangle

- Unitarity of V_{CKM} ➡ $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = 1$ ➡ $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$
  - This is neatly represented by the familiar Unitarity Triangle



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}} \right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}} \right)$$

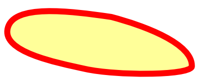
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} \right)$$

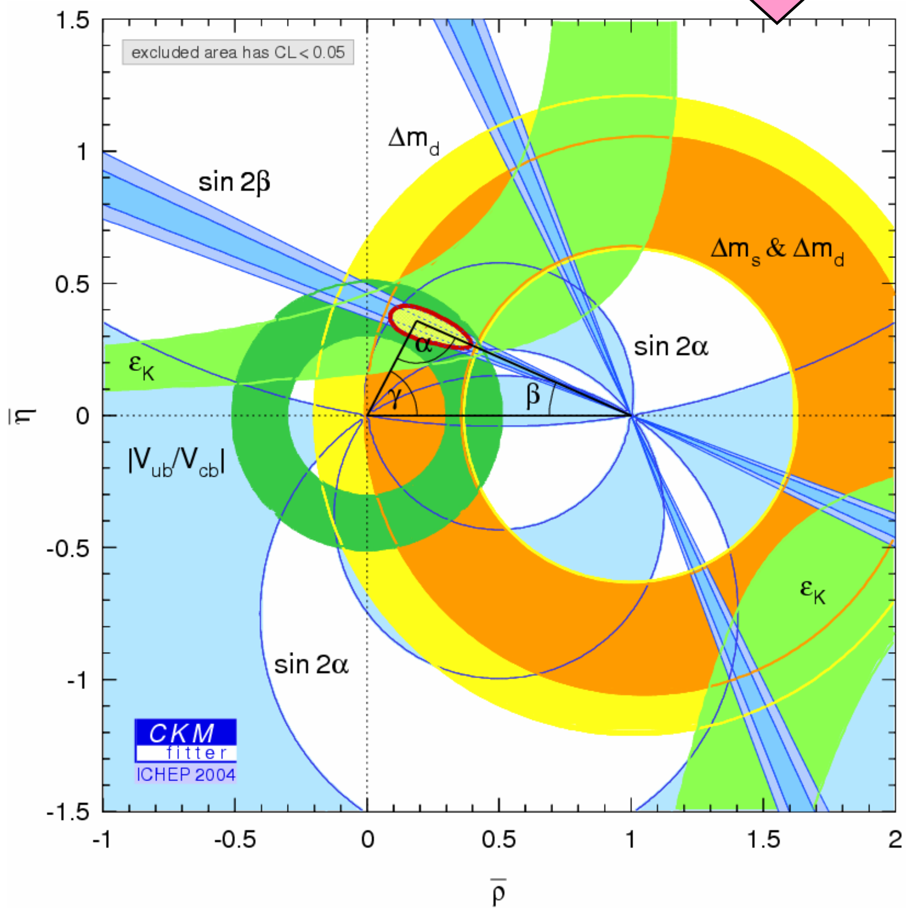
  - Angles α, β, γ can be measured with CPV of B decays

Coming soon:

Measurements of β from BABAR, by Soeren Prell, 1/20/05
Measurements of α and γ from BABAR, by Malcolm John, 2/20/05

Consistency Test

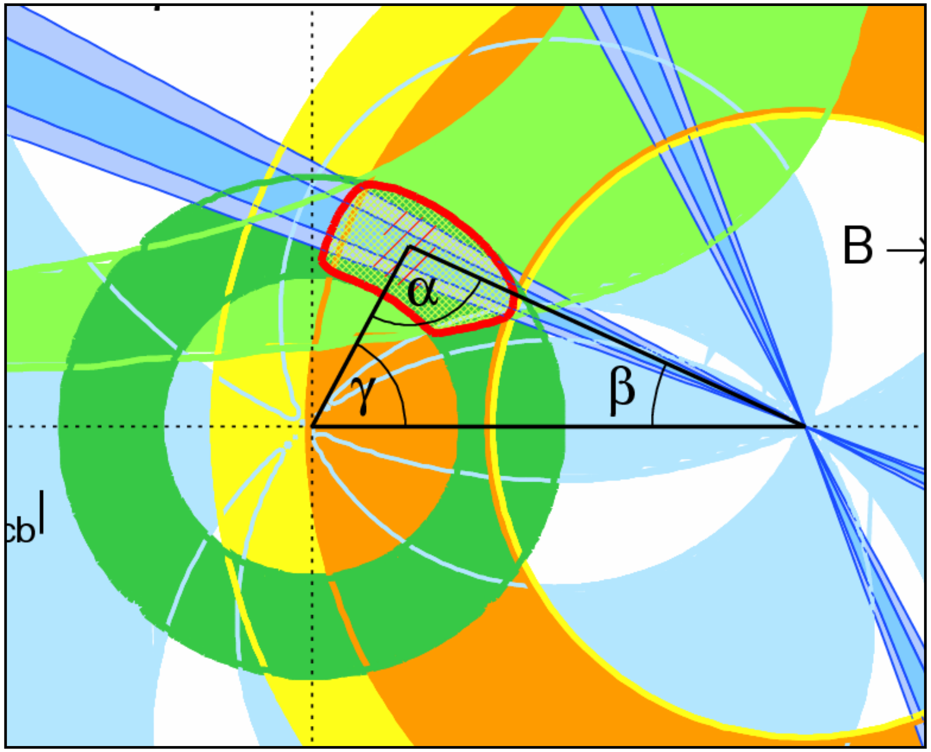
- Compare the measurements (contours) on the (ρ, η) plane
  - If the SM is the whole story, they must all overlap
- The  tells us this is true as of today
  - Still large enough for New Physics to hide
- Precision of sin2β outstripped the other measurements
  - Must improve the others to make more stringent test



Next Step: $|V_{ub}/V_{cb}|$

- Zoom in to see the overlap of "the other" contours
  - It's obvious: we must make the green ring thinner
- Left side of the Triangle is

$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \left|\frac{V_{ub}}{V_{cb}}\right| \frac{1}{\tan\theta_C}$$

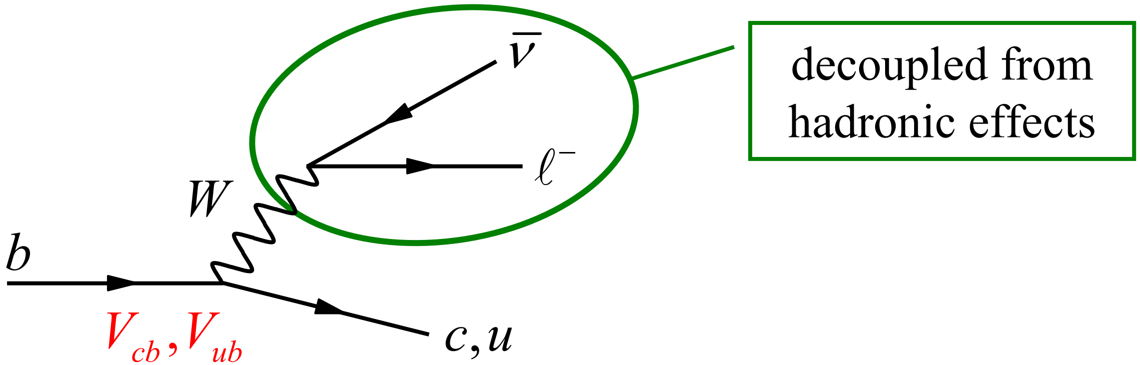


Measurement of $|V_{ub}/V_{cb}|$ is complementary to $\sin 2\beta$

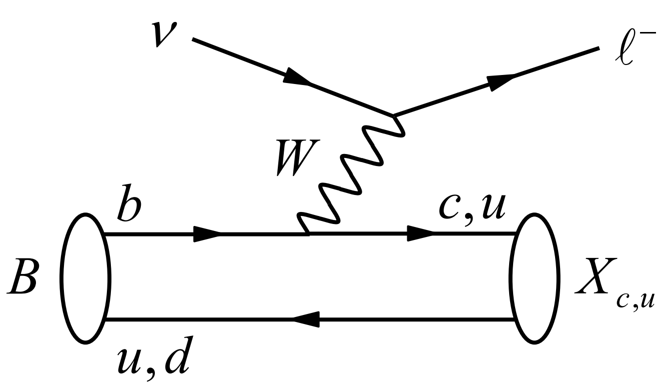
Goal: Accurate determination of both $|V_{ub}/V_{cb}|$ and $\sin 2\beta$

Semileptonic *B* Decays

- Semileptonic decays offer a clear view of the *b* quark in the *B* mesons



- Analogous to deep-inelastic scattering



  - Good probe for $|V_{cb}|$ and $|V_{ub}|$
  - We can also study the structure of the *B* meson

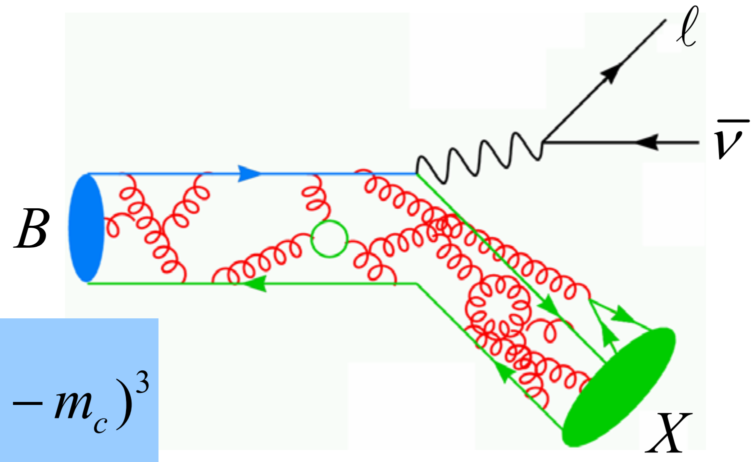
More on this as we go

Experimental Approaches

- Inclusive: $B \to X_c \ell \nu$ or $X_u \ell \nu$
  - Tree-level rates are

$$\Gamma_u \equiv \Gamma(b \to u \ell \nu) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5$$

$$\Gamma_c \equiv \Gamma(b \to c \ell \nu) = \frac{G_F^2}{192\pi^2} |V_{cb}|^2 m_b^2 (m_b - m_c)^3$$



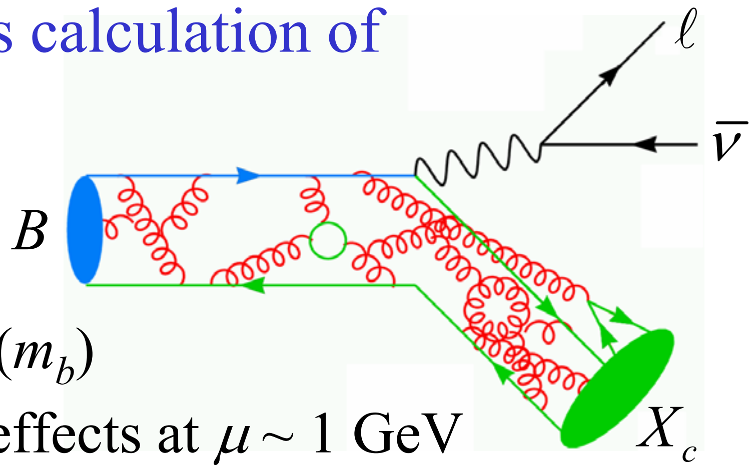
  - QCD corrections must be calculated
    - Operator Product Expansion (OPE)
  - How do we separate X_u from X_c?
    - $\Gamma_c = 50 \times \Gamma_u$ ➔ Much harder problem for $|V_{ub}|$

Focus of this talk

- Exclusive: $B \to D^* \ell \nu$, $D \ell \nu$, $\pi \ell \nu$, $\rho \ell \nu$, etc.
  - Need form factors to relate the rate to $|V_{cb}|$, $|V_{ub}|$

Inclusive $|V_{cb}|$

- Operator Product Expansion allows calculation of
  - Inclusive rate
  - Lepton energy (E_ℓ) moments
  - Hadron mass (m_X) moments



  - Expansion in terms of $1/m_b$ and $\alpha_s(m_b)$
  - Separate short- and long-distance effects at $\mu \sim 1$ GeV
    - Perturbative corrections calculable from m_b, m_c, $\alpha_s(m_b)$
    - Non-perturbative corrections cannot be calculated
      - Ex: 4 parameters up to $\mathcal{O}(1/m_b^3)$ in the kinetic scheme
- Strategy: Measure rate + as many moments as possible
  - Determine all parameters by a global fit
  - Over-constrain to validate the method

Observables

- Define 8 moments from inclusive E_ℓ and m_X spectra

$$M_0^\ell = \frac{\int d\Gamma}{\Gamma_B}$$

Partial branching fraction

$$M_1^\ell = \frac{\int E_\ell d\Gamma}{\int d\Gamma} \qquad M_i^\ell = \frac{\int \left(E_\ell - M_1^\ell\right)^i d\Gamma}{\int d\Gamma} \quad (i = 2,3)$$

Lepton energy moments

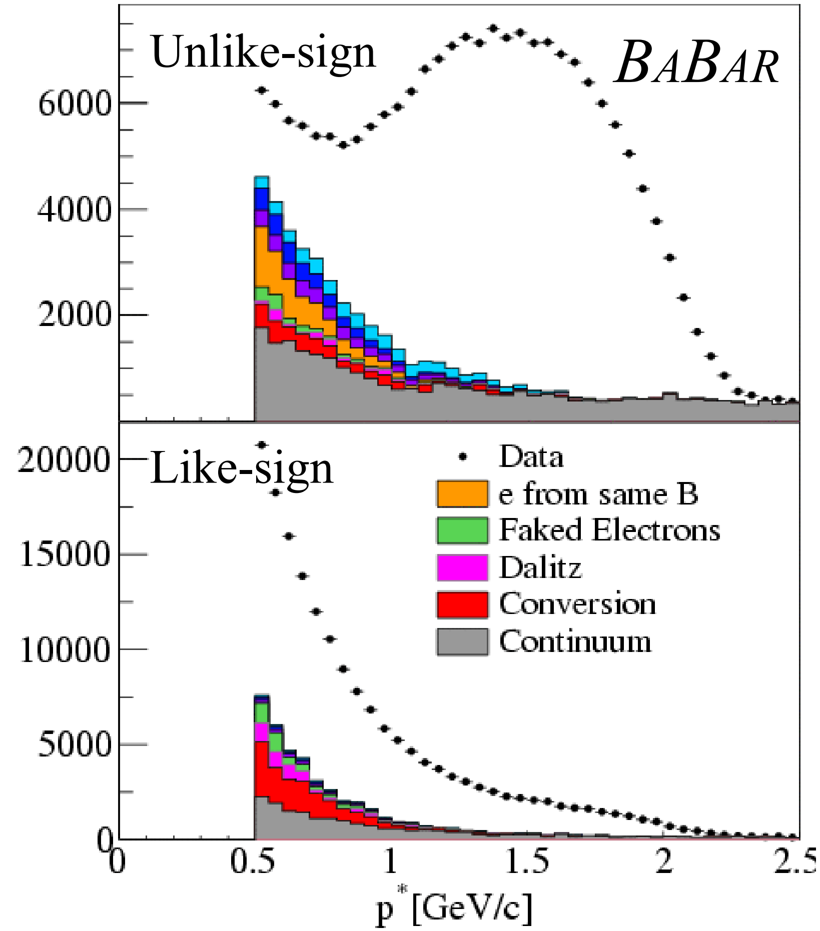
$$M_i^X = \frac{\int m_X^i d\Gamma}{\int d\Gamma} \quad (i = 1,2,3,4)$$

Hadron mass moments

  - Integrations are done for $E_\ell > E_{cut}$, with E_{cut} varied in 0.6–1.5 GeV

Electron Energy Moments

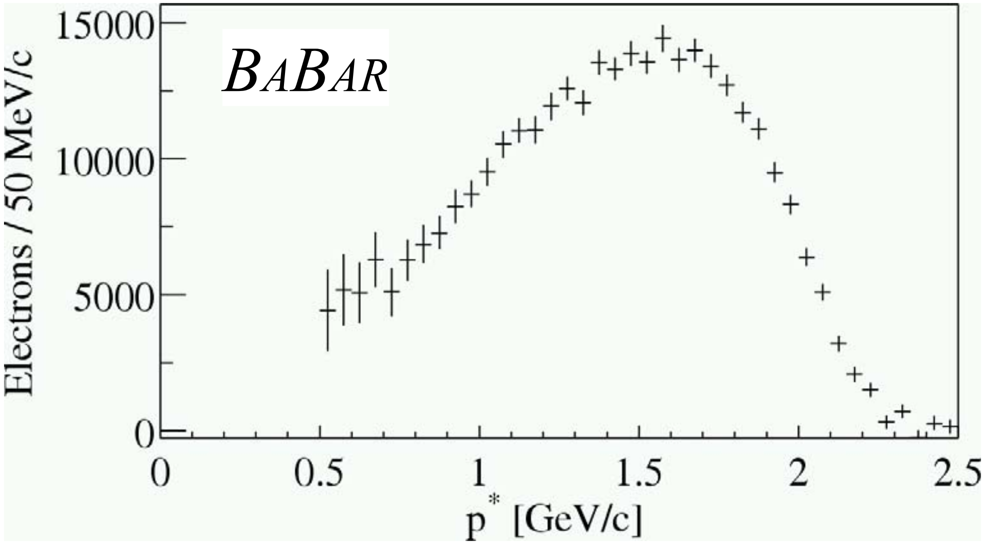
- BABAR data, 47.4 fb^{-1} on $\Upsilon(4S)$ resonance + 9.1 fb^{-1} off-peak
- Select events with 2 electrons
  - One ($1.4 < p^* < 2.3$ GeV) to "tag" a $\bar{B}B$ event
  - The other ($p^* > 0.5$ GeV) to measure the spectrum
- Use charge correlation
  - Unlike-sign events
    - dominated by $B \to X_c e\nu$
  - Like-sign events
    - $D \to Xe\nu$ decays, B^0 mixing



BABAR PR D69:111104

Electron Energy Moments

- Turn the like-/unlike-sign spectra → E_ℓ spectrum
  - Divide by the efficiency
  - Account for B^0 mixing
  - Correct for the detector material (Bremsstrahlung)

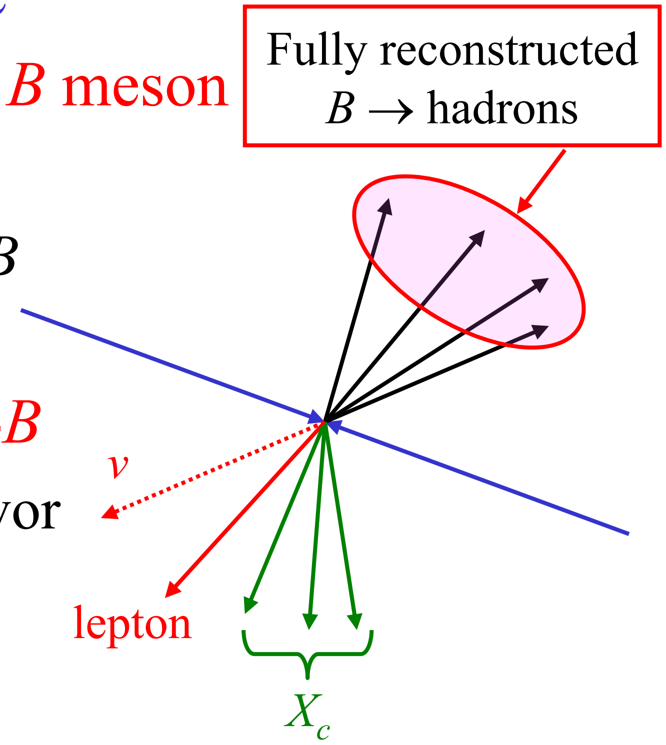


- Calculate the moments for $E_{cut} = 0.6 \ldots 1.5$ GeV
  - Move from ϒ(4*S*) to *B* rest frame
  - Correct for the final state radiation using PHOTOS
  - Subtract $B \to X_u \ell \nu$

Into the OPE fit

Hadron Mass Moments

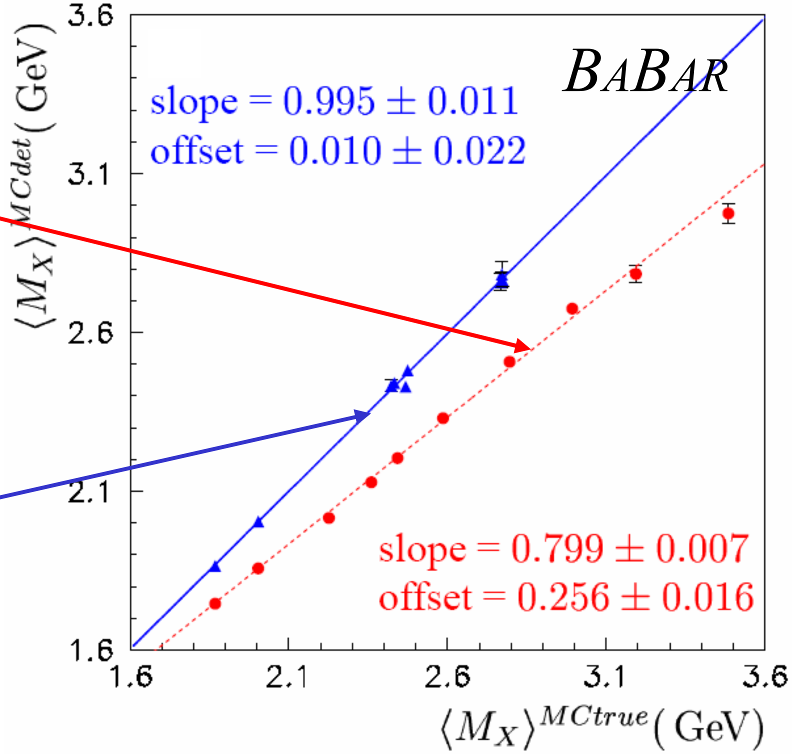
- BaBar data, 81 fb^{-1} on $\Upsilon(4S)$ resonance
- Select events with a fully-reconstructed B meson
  - Use ~1000 hadronic decay chains
  - Rest of the event contains one "recoil" B
    - Flavor and momentum known
- Find a lepton with $E > E_{cut}$ in the recoil-B
  - Lepton charge consistent with the B flavor
  - m_{miss} consistent with a neutrino
- All left-over particles belong to X_c
  - Improve m_X with a kinematic fit → $\sigma = 350$ MeV
    - 4-momentum conservation; equal m_B on both sides; $m_{\text{miss}} = 0$



BaBar PR D69:111103

Hadron Mass Moments

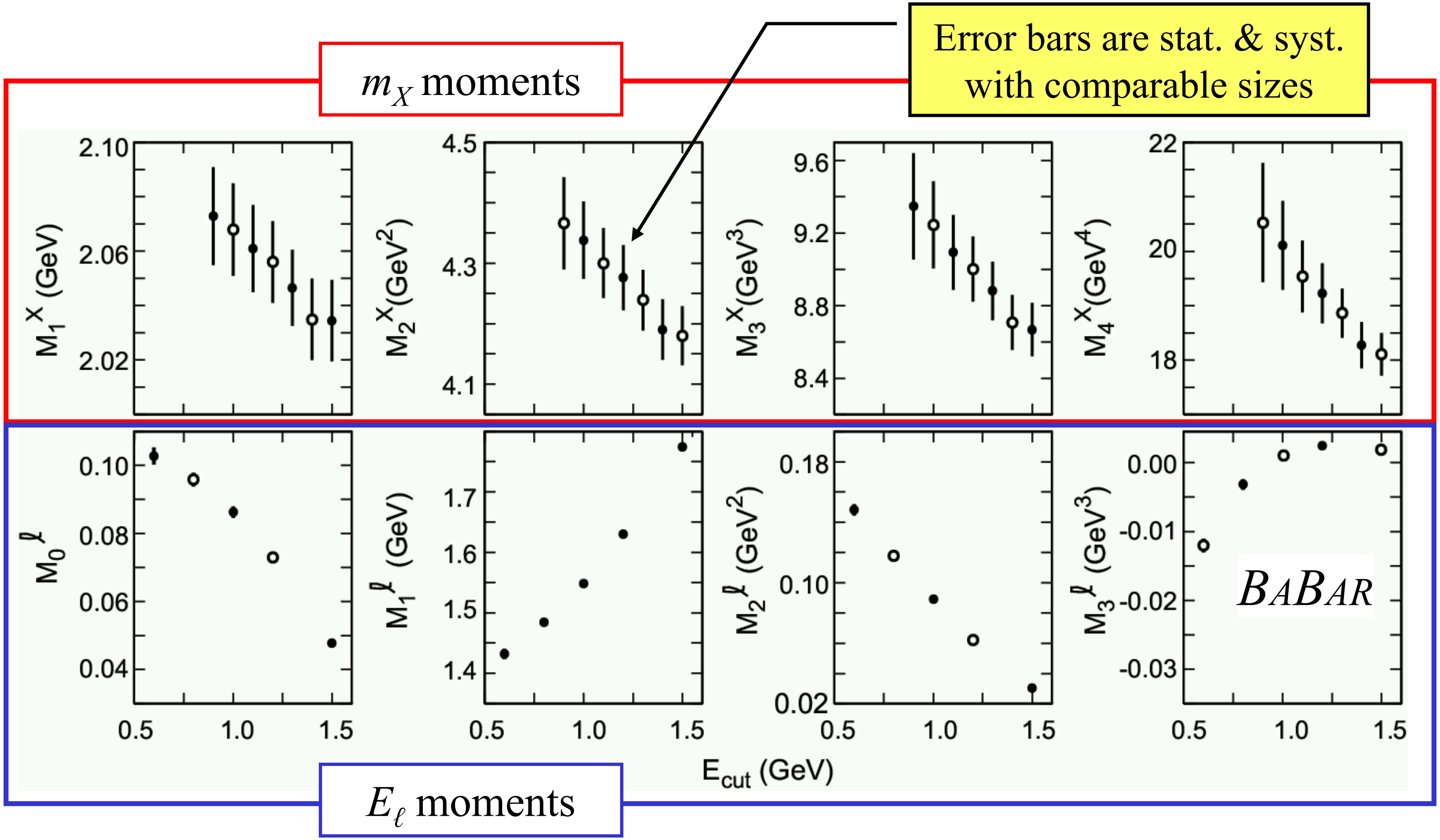
- Measured $m_X <$ true m_X
  - Linear relationship
    → Calibrate using simulation
    - Depends (weakly) on decay multiplicity and m^2_{miss}
- Validate calibration procedure
  - Simulated events in exclusive final states
  - $D^{*\pm} \to D^0\pi^\pm$ in real data, tagged by the soft $\pi^\pm$



- Calculate mass moments with $E_{cut} = 0.9 \ldots 1.6$ GeV

Into the OPE fit

Inputs to OPE Fit



BABAR PRL 93:011803

Fit Parameters

- Calculation by Gambino & Uraltsev (hep-ph/0401063 & 0403166)
  - Kinetic mass scheme to $\mathcal{O}(1/m_b^3)$
  - E_ℓ moments $\mathcal{O}(\alpha_s^2)$
  - m_X moments $\mathcal{O}(\alpha_s)$
- 8 parameters to determine

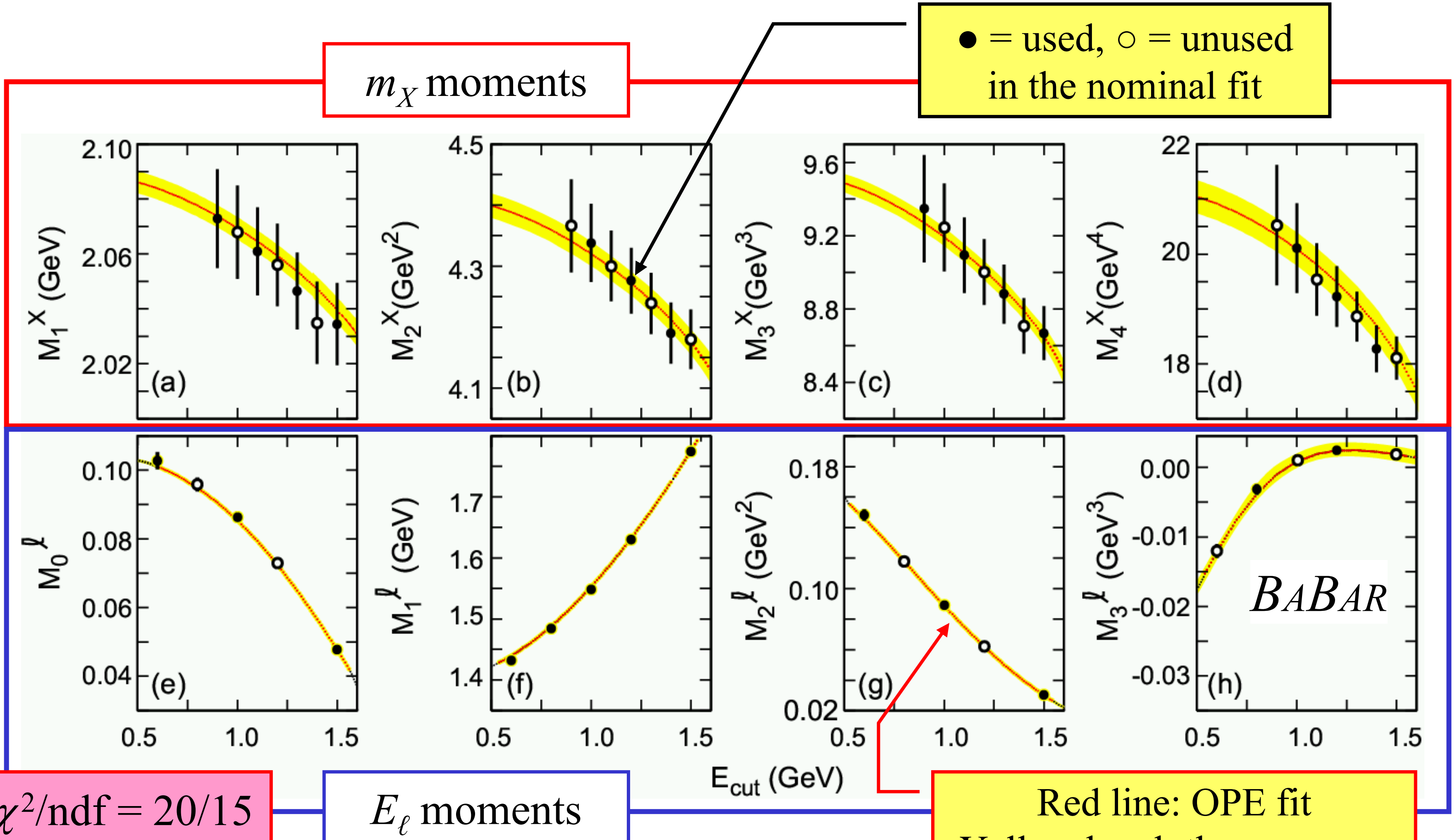
$|V_{cb}|$ m_b m_c $\mathcal{B}(B \to X_c \ell \nu)$ μ_π^2 μ_G^2 ρ_D^3 ρ_{LS}^3

kinetic, chromomagnetic: $\mathcal{O}(1/m_b^2)$

spin-orbit, Darwin: $\mathcal{O}(1/m_b^3)$

- 8 moments available with several E_{cut}
  - Sufficient degrees of freedom to determine all parameters without external inputs
  - Fit quality tells us how well OPE works

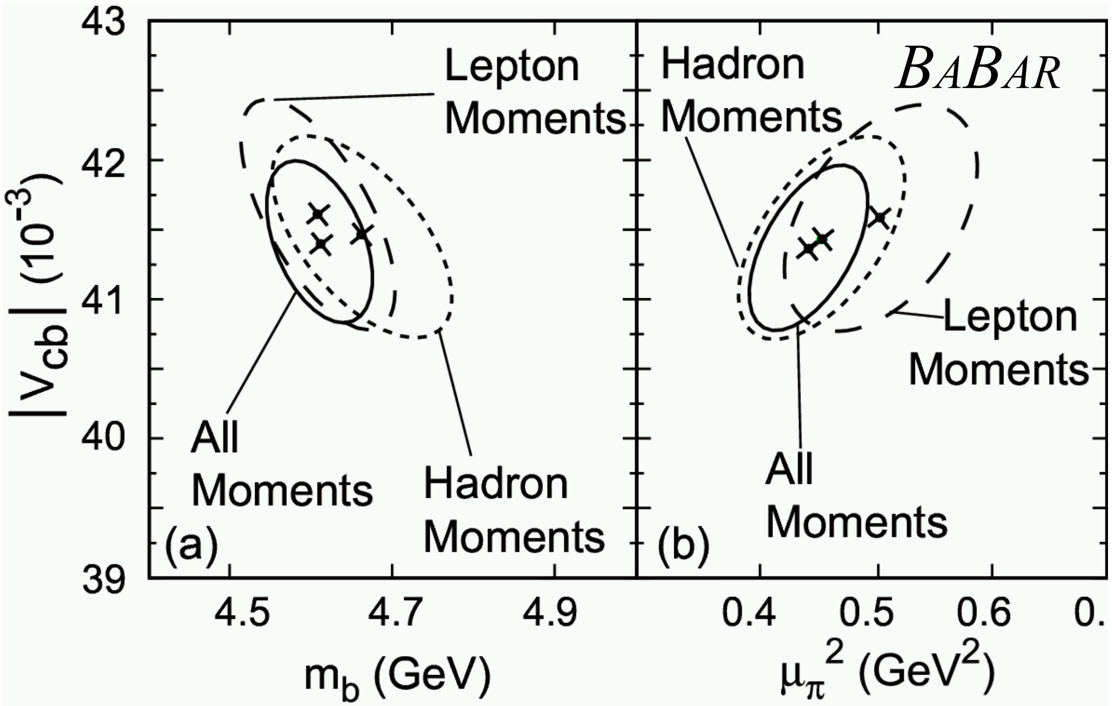
Fit Results



χ^2/ndf = 20/15

Fit Consistency

- OPE describes BABAR data very well
  - $\chi^2/\text{ndf} = 20/15$
  - Separate fit of E_ℓ and m_X moments agree



Fit Results

$$|V_{cb}| = (41.4 \pm 0.4_{\text{exp}} \pm 0.4_{\text{HQE}} \pm 0.6_{\text{th}}) \times 10^{-3}$$

Uncalculated corrections to Γ

$$\mathcal{B}_{c\ell\nu} = (10.61 \pm 0.16_{\text{exp}} \pm 0.06_{\text{HQE}})\%$$

$$m_b = (4.61 \pm 0.05_{\text{exp}} \pm 0.04_{\text{HQE}} \pm 0.02_{\alpha_s})\,\text{GeV}$$

$$m_c = (1.18 \pm 0.07_{\text{exp}} \pm 0.06_{\text{HQE}} \pm 0.02_{\alpha_s})\,\text{GeV}$$

$$\mu_\pi^2 = (0.45 \pm 0.04_{\text{exp}} \pm 0.04_{\text{HQE}} \pm 0.01_{\alpha_s})\,\text{GeV}^2$$

$$\mu_G^2 = (0.27 \pm 0.06_{\text{exp}} \pm 0.03_{\text{HQE}} \pm 0.02_{\alpha_s})\,\text{GeV}^2$$

$$\rho_D^3 = (0.20 \pm 0.02_{\text{exp}} \pm 0.02_{\text{HQE}} \pm 0.00_{\alpha_s})\,\text{GeV}^3$$

$$\rho_{LS}^3 = (-0.09 \pm 0.04_{\text{exp}} \pm 0.07_{\text{HQE}} \pm 0.01_{\alpha_s})\,\text{GeV}^3$$

kinetic mass scheme with $\mu = 1$ GeV

- μ_π^2 and ρ_{LS}^3 consistent with B-B^* mass splitting and QCD sum rules
- $\mu_\pi^2 > \mu_G^2$ and the scale of ρ_D^3 consistent with theoretical expectations

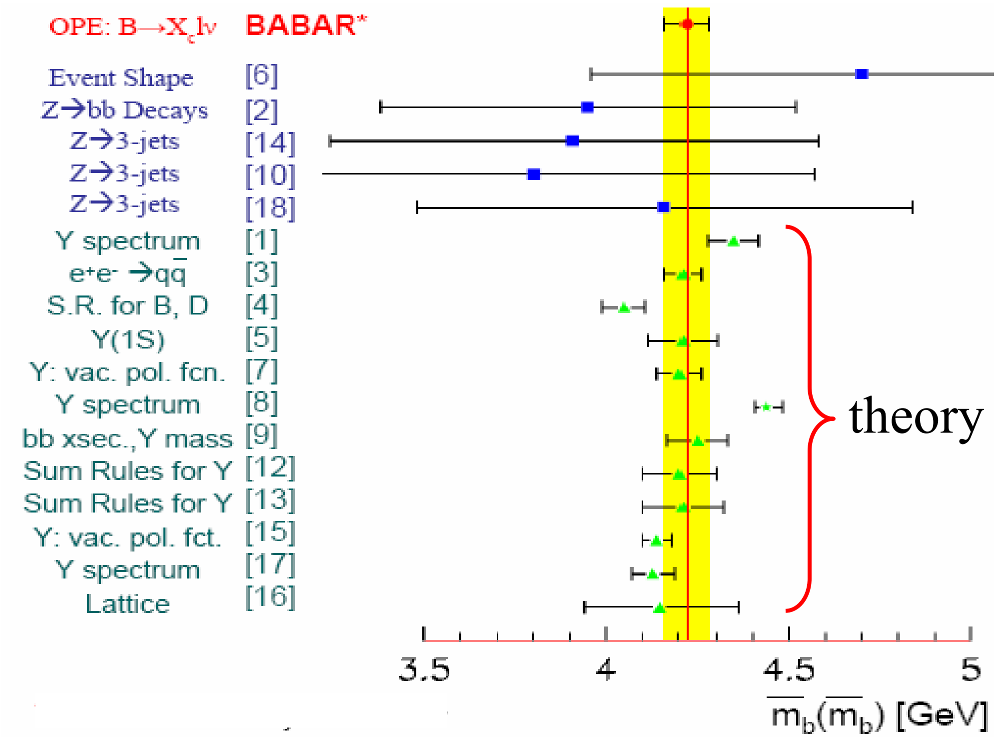
- Remarkable agreement between data and theory

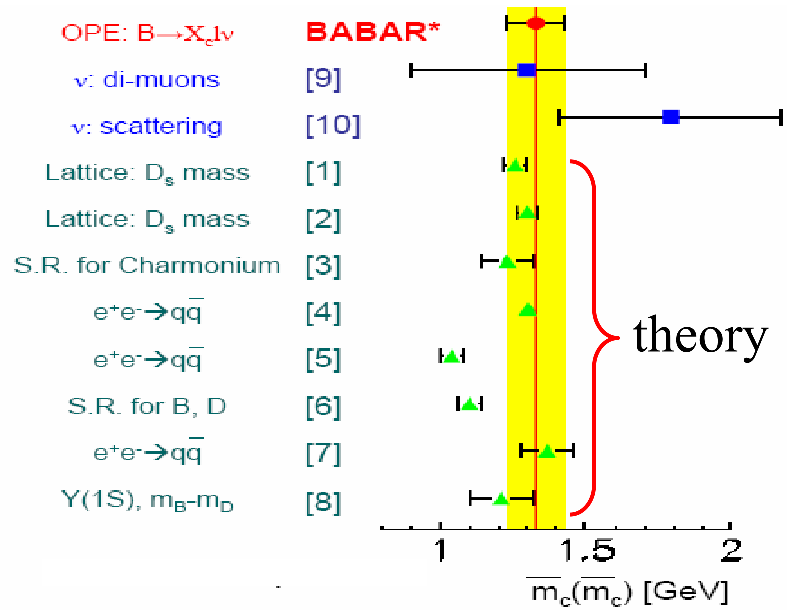
Heavy Quark Masses

- Convert m_b and m_c into $\overline{\mathrm{MS}}$ scheme (N. Uraltsev)

$$m_b^{\mathrm{kin}}(1\,\mathrm{GeV}) = (4.61 \pm 0.05_{\mathrm{exp}} \pm 0.04_{\mathrm{HQE}} \pm 0.02_{\mathrm{th}})\,\mathrm{GeV}$$
$$m_c^{\mathrm{kin}}(1\,\mathrm{GeV}) = (1.18 \pm 0.07_{\mathrm{exp}} \pm 0.06_{\mathrm{HQE}} \pm 0.02_{\mathrm{th}})\,\mathrm{GeV}$$

$$\overline{m}_b(\overline{m}_b) = 4.22 \pm 0.06\,\mathrm{GeV}$$
$$\overline{m}_c(\overline{m}_c) = 1.33 \pm 0.10\,\mathrm{GeV}$$

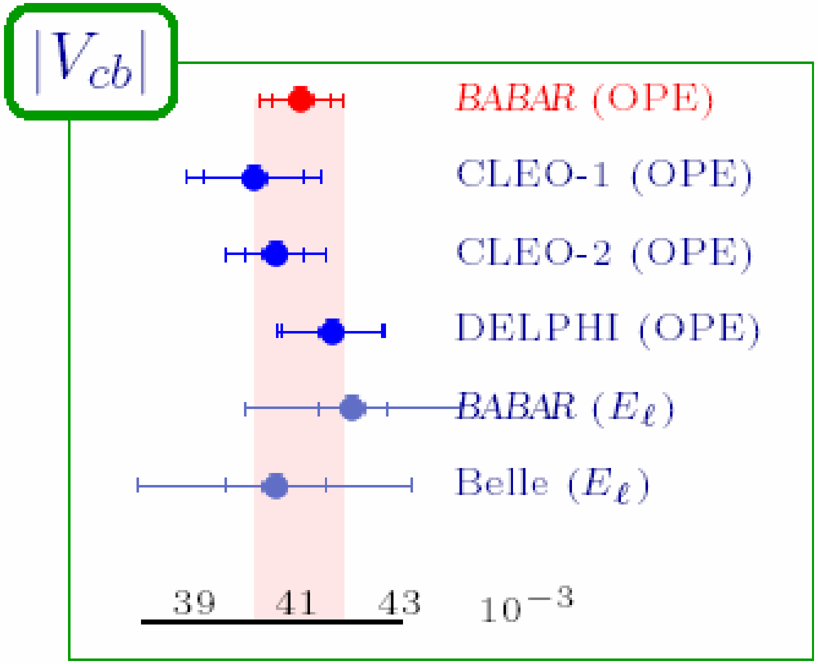


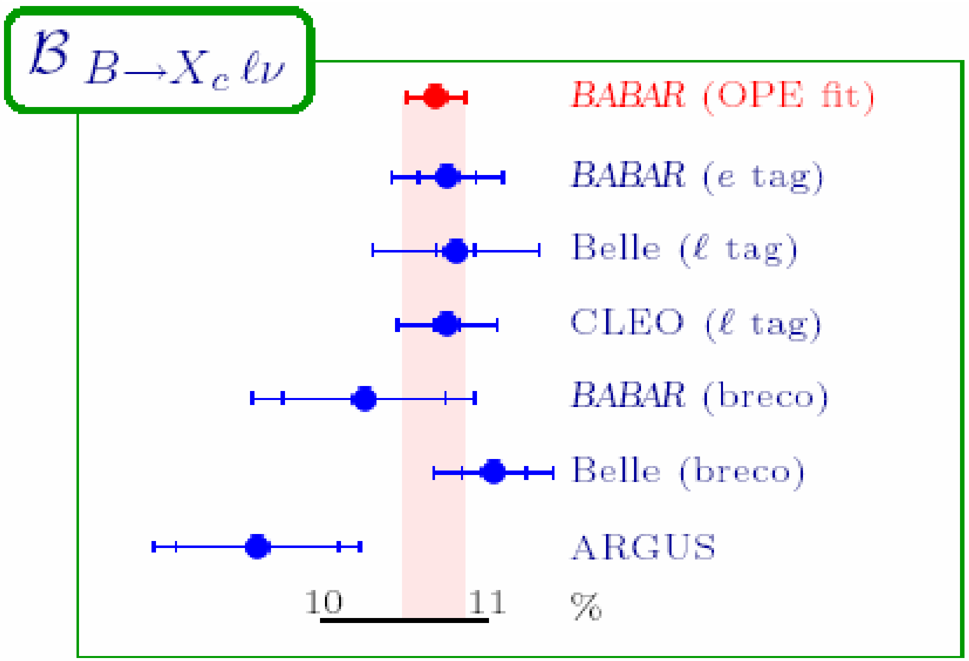


References in PDG 2002

Inclusive $|V_{cb}|$ in Perspective

- BABAR result compares well with previous measurements





- $|V_{cb}|$ is now measured to ±2%

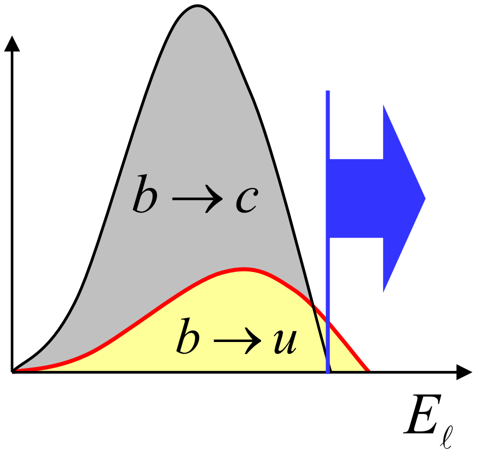
Inclusive $|V_{ub}|$

- $|V_{ub}|$ can be measured from $\Gamma_u \equiv \Gamma(b \to u \ell \nu) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5$
- The problem: $b \to c\ell\nu$ decay

$$\frac{\Gamma(b \to u \ell \bar{\nu})}{\Gamma(b \to c \ell \bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$

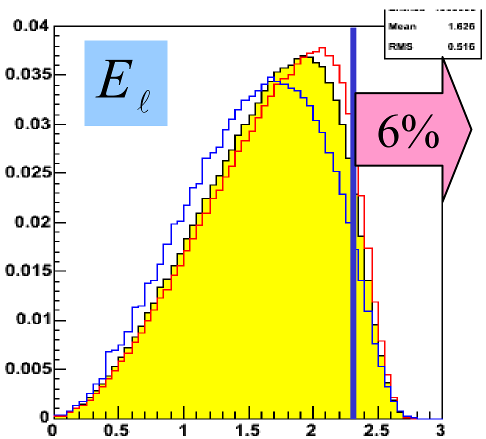
How can we suppress 50× larger background?

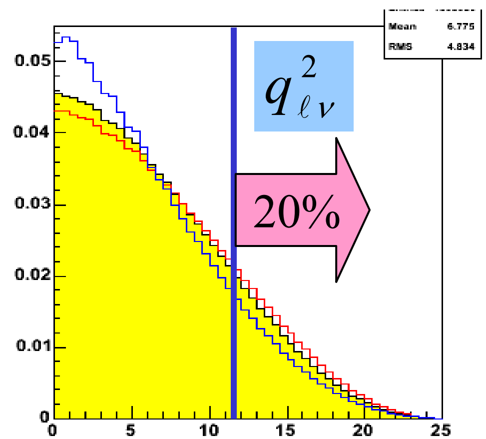
- Use $m_u << m_c$ → difference in kinematics
  - Maximum lepton energy 2.64 vs. 2.31 GeV
  - First observations (CLEO, ARGUS, 1990) used this technique
  - Only 6% of signal accessible
    - How accurately do we know this fraction?

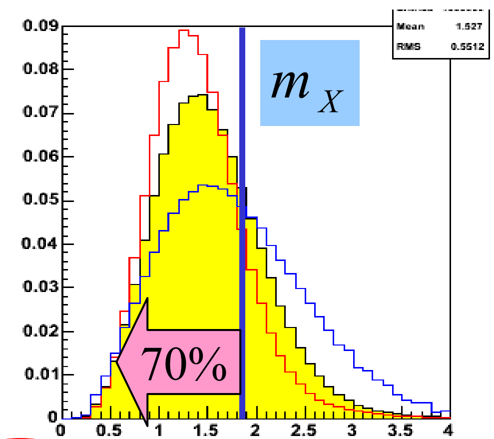


$b \to u\ell\nu$ Kinematics

- There are 3 independent variables in $B \to X\ell\nu$
  - Take E_ℓ, q^2 (lepton-neutrino mass^2), and m_X (hadronic mass)





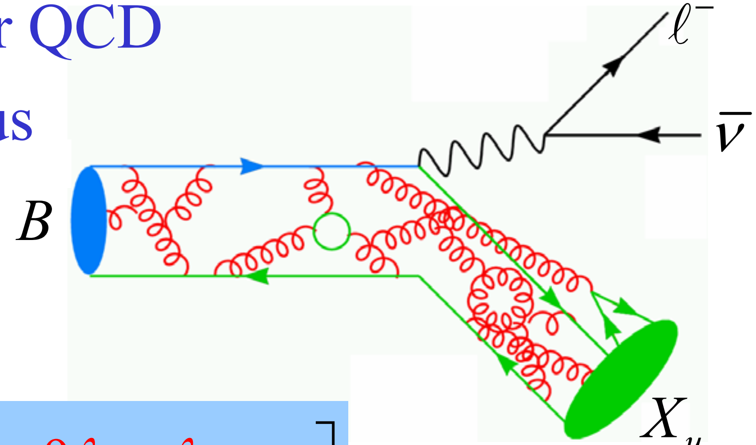


	Technique	Efficiency	Theoretical Error
E_ℓ	Straightforward	Low	Large
q^2	Complicated	Moderate	Moderate
m_X	Complicated	High	Large

Where does it come from?

Theoretical Issues

- Tree level rate must be corrected for QCD
- Operator Product Expansion gives us the inclusive rate
  - Expansion in $\alpha_s(m_b)$ (perturbative) and $1/m_b$ (non-perturbative)



$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 - \mathcal{O}\left(\frac{\alpha_s}{\pi}\right) - \frac{9\lambda_2 - \lambda_1}{2m_b^2} + \cdots\right]$$

known to $\mathcal{O}(\alpha_s{}^2)$

Suppressed by $1/m_b{}^2$

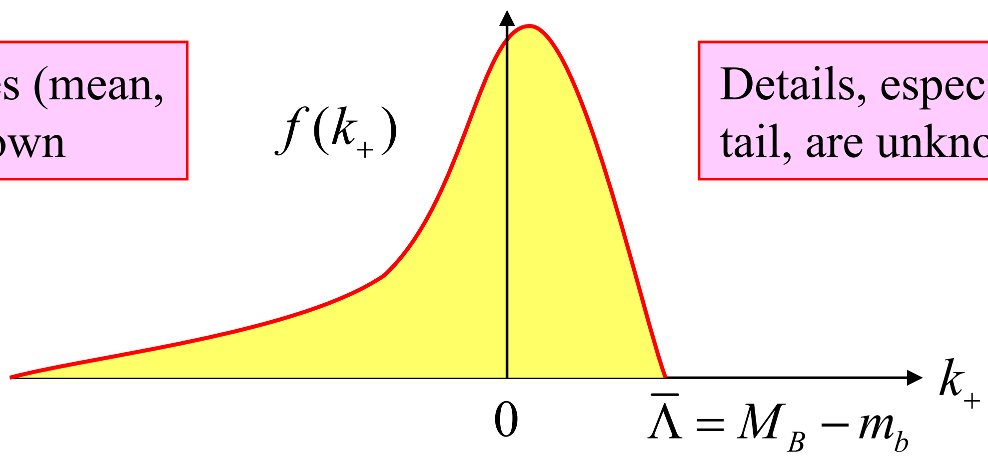
  - Main uncertainty (±10%) from $m_b{}^5$ → ±5% on $|V_{ub}|$

- But we need the accessible fraction (e.g., $E_\ell > 2.3$ GeV) of the rate

Shape Function

- OPE doesn't work everywhere in the phase space
  - OK once integrated
  - Doesn't converge, e.g., near the E_ℓ end point
- Resumming turns non-perturb. terms into a Shape Function
  - ≈ b quark Fermi motion parallel to the u quark velocity
  - Smears the quark-level distribution → observed spectra

Rough features (mean, r.m.s.) are known

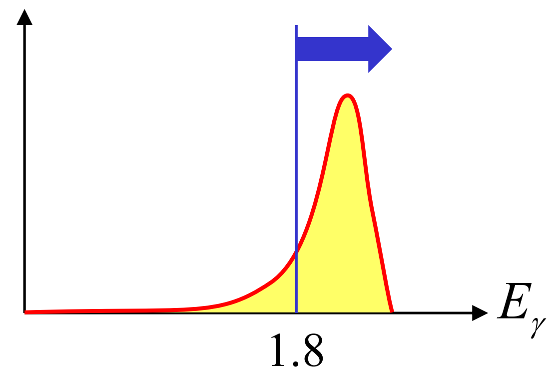


Details, especially the tail, are unknown

Shape Function – What to Do?

- Measure: Same SF affects (to the first order) $b \to s\gamma$ decays

Measure E_γ spectrum in $b \to s\gamma$ → Extract $f(k_+)$ → Predict E_ℓ spectrum in $b \to u\ell\nu$



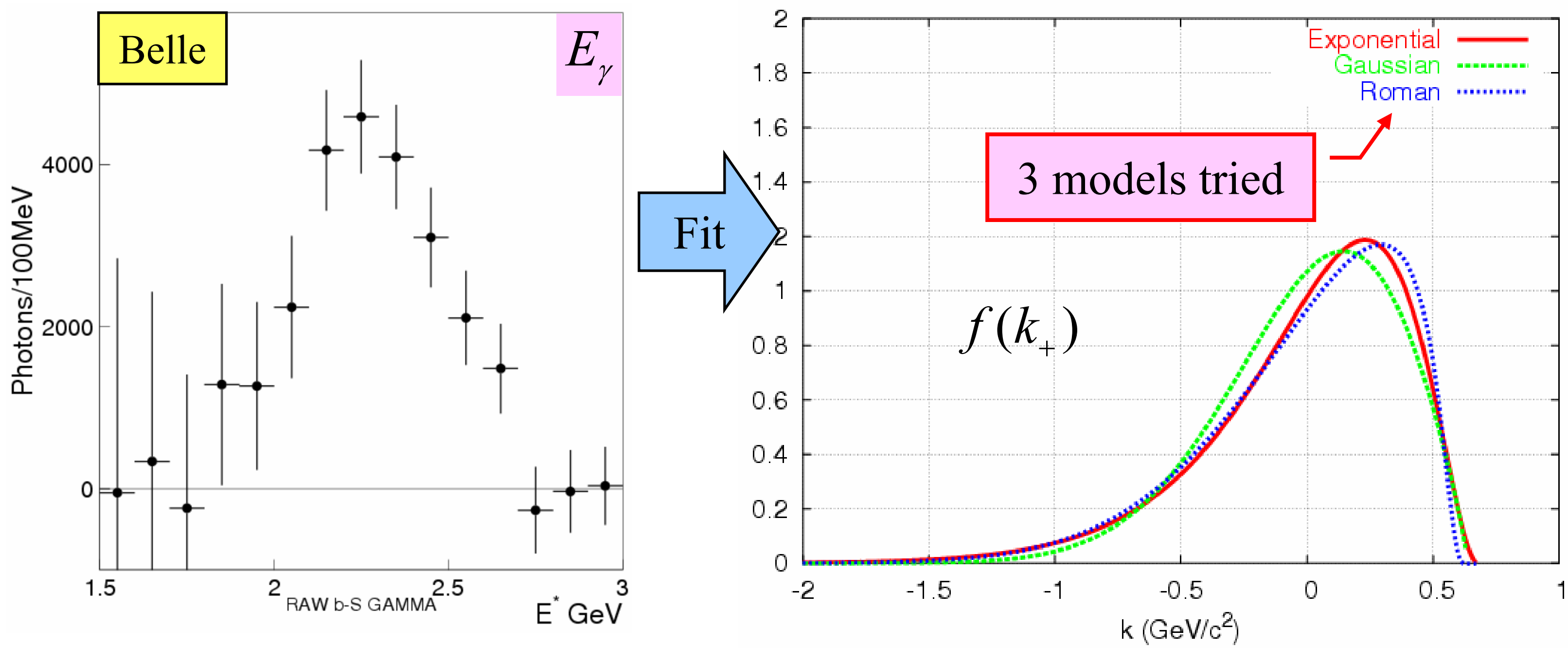
  - Caveat: whole E_γ spectrum is needed
    - Only $E_\gamma > 1.8$ GeV has been measured
    - Background overwhelms lower energies
  - Compromise: assume functional forms of $f(k_+)$
    - Example: $f(k_+) = N(1-x)^a e^{(1+a)x}; \quad x = \frac{k_+}{\bar{\Lambda}}$ ← 2 parameters (Λ and a) to fit
    - Fit $b \to s\gamma$ spectrum to determine the parameters
    - Try different functions to assess the systematics

SF from $b \to s\gamma$

CLEO hep-ex/0402009

Belle hep-ex/0407052

- CLEO and Belle has measured the $b \to s\gamma$ spectrum
  - BABAR result on the way



- I use the SF from the Belle data for the rest of the talk

Measurements

- BaBar has measured $|V_{ub}|$ using four different approaches

Technique	Reference
$E_\ell > 2.0$ GeV	hep-ex/0408075
E_ℓ vs. q^2	hep-ex/0408045
$m_X < 1.55$ GeV	hep-ex/0408068
m_X vs. q^2	

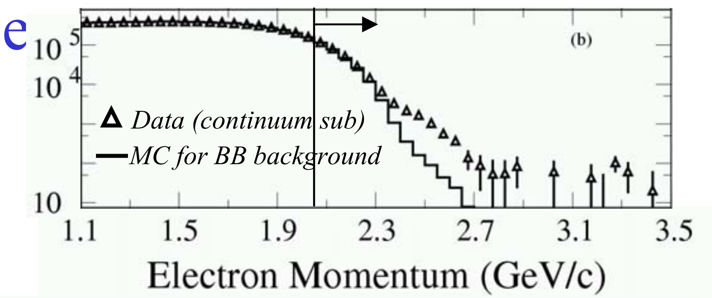
Inclusive $B \to Xev$ sample.
High statistics, low purity.

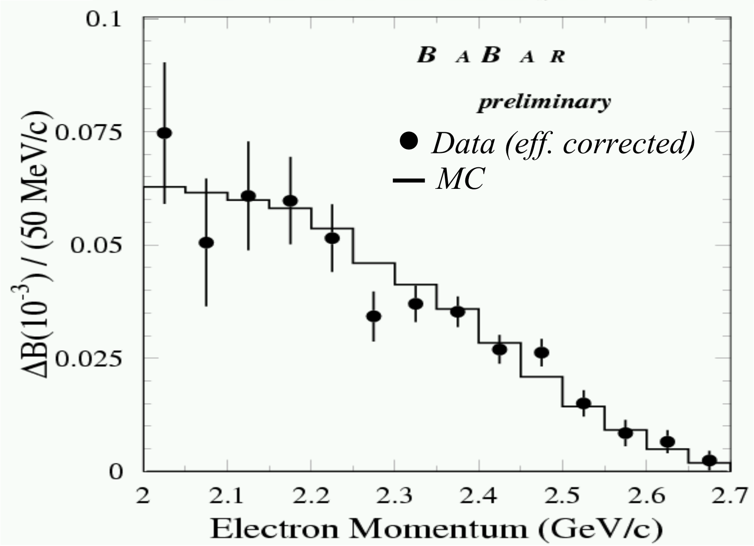
Recoil of fully-reconstructed B.
High purity, moderate statistics.

  - Statistical correlations are small
  - Different systematics, different theoretical errors

Lepton Endpoint

- BABAR data, 80 fb^{-1} on $\Upsilon(4S)$ resonance
- Select electrons in $2.0 < E_\ell < 2.6$ GeV
  - Push below the charm threshold
    - ➔ Larger signal acceptance
    - ➔ Smaller theoretical error
- Accurate subtraction of background is crucial!
  - Data taken below the Υ_{4S} resonance for light-flavor background
  - Fit the E_ℓ spectrum with $b \to u\ell\nu$, $B \to D\ell\nu$, $B \to D^*\ell\nu$, $B \to D^{**}\ell\nu$, etc. to measure





$$\Delta\mathcal{B}(B \to X_u e\nu, E_e > 2.0\,\mathrm{GeV}) = (4.85 \pm 0.29_{\mathrm{stat}} \pm 0.53_{\mathrm{sys}}) \times 10^{-4}$$

BABAR hep-ex/0408075
CLEO PRL 88:231803
BELLE-CONF-0325

Lepton Endpoint

- Translate $\Delta\mathcal{B}$ into $|V_{ub}|$
  - Compare results with different E_ℓ cut

	E_ℓ (GeV)	$\Delta\mathcal{B}$ (10^{-4})	$\lvert V_{ub}\rvert$ (10^{-3})
BABAR	2.0–2.6	$4.85 \pm 0.29_{\mathrm{stat}} \pm 0.53_{\mathrm{sys}}$	$4.40 \pm 0.13_{\mathrm{stat}} \pm 0.25_{\mathrm{sys}} \pm 0.38_{\mathrm{theo}}$
CLEO	2.2–2.6	$2.30 \pm 0.15_{\mathrm{exp}} \pm 0.35_{\mathrm{sys}}$	$4.69 \pm 0.15_{\mathrm{stat}} \pm 0.40_{\mathrm{sys}} \pm 0.52_{\mathrm{theo}}$
Belle	2.3–2.6	$1.19 \pm 0.11_{\mathrm{exp}} \pm 0.10_{\mathrm{sys}}$	$4.46 \pm 0.20_{\mathrm{stat}} \pm 0.22_{\mathrm{sys}} \pm 0.59_{\mathrm{theo}}$

  - Theoretical error reduced with lower E_ℓ cut

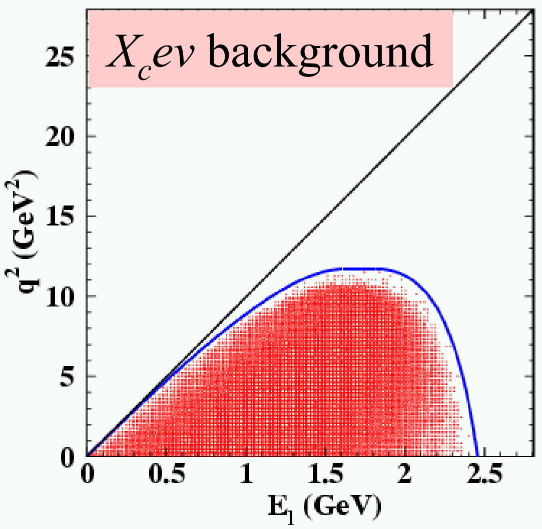
E_ℓ vs. q^2

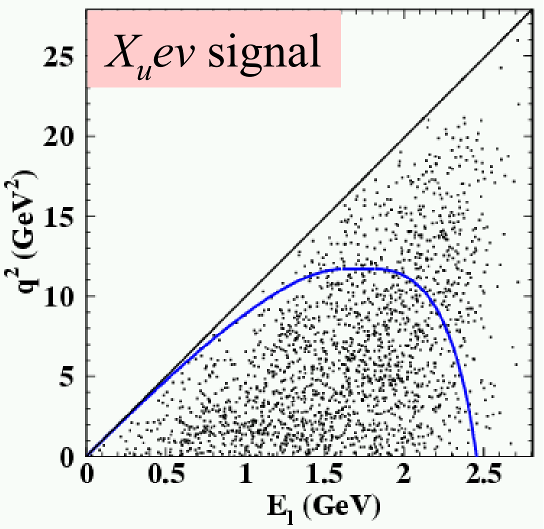
- Use $\mathbf{p}_\nu = \mathbf{p}_{\text{miss}}$ in addition to $\mathbf{p}_e$ → Calculate q^2
  - Given E_e and q^2, maximum hadronic mass squared is

$$s_h^{\max} = \begin{cases} m_B^2 + q^2 - 2m_B E_e \sqrt{\frac{1\mp\beta}{1\pm\beta}} - 2m_B \frac{q^2}{4E_e}\sqrt{\frac{1\pm\beta}{1\mp\beta}} & \text{if } \pm E_e > \pm\frac{\sqrt{q^2}}{2}\frac{1\pm\beta}{1\mp\beta} \\ m_B^2 + q^2 - 2m_B\sqrt{q^2} & \text{otherwise} \end{cases}$$

$\beta = B$ boost in the c.m.s.

  - $\boxed{s_h^{\max} < m_D^2}$ gives optimum separation of $B \to X_u e\nu$ from $X_c e\nu$





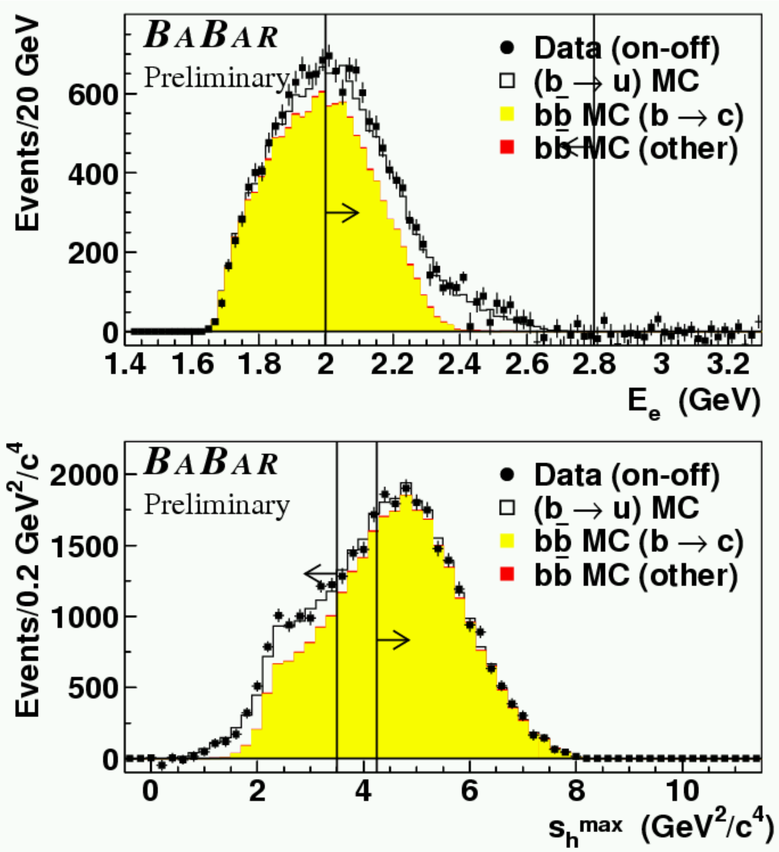
E_ℓ vs. q^2

- BABAR data, 80 fb^{-1} on resonance
  - Subtract off-peak data
  - Subtract BB background normalized by sideband
  - Signal efficiency corrected by $B \to D^{(*)} e\nu$ control samples
- Inclusive BF measured to be

$$\mathcal{B} = (2.76 \pm 0.26_{\text{stat}} \pm 0.50_{\text{syst}} {}^{+0.21}_{-0.26}{}_{\text{SF}}) \times 10^{-3}$$

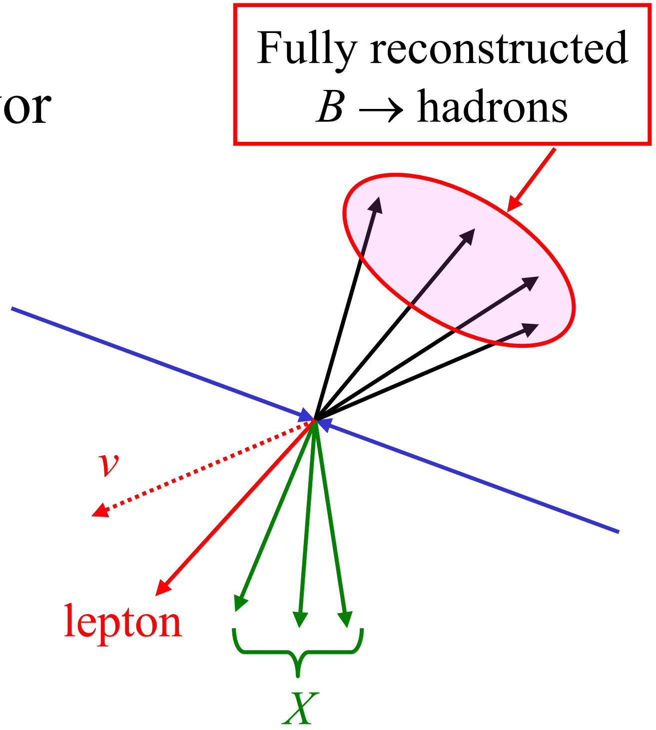
- Translate to $|V_{ub}|$

$$|V_{ub}| = (4.99 \pm 0.48_{\text{exp}} {}^{+0.18}_{-0.23}{}_{\text{SF}} \pm 0.22_{\text{OPE}}) \times 10^{-3}$$



Measuring m_X and q^2

- Same recoil technique as the $b \to c\ell\nu$ m_X moment measurement
  - Find a lepton ($p_\ell > 1\text{GeV}$) in recoil B
  - Lepton charge consistent with the B flavor
  - m_{miss} consistent with a neutrino
- All left-over particles belong to X
  - Improve m_X with a kinematic fit
  - Calculate q^2 of lepton-neutrino
- Sample is mostly $b \to c\ell\nu$ at this stage
  - Need some charm rejection cuts

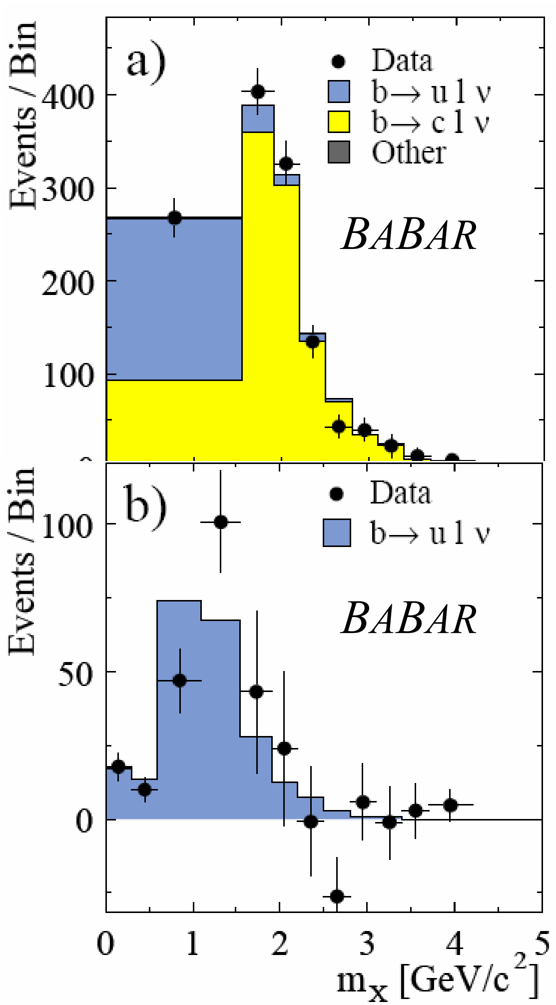


Charm Suppression

- Suppress $b \to c\ell\nu$ by vetoing against $D^{(*)}$ decays
  - D decays usually produce at least one kaon
    ➔ Reject events with $K^{\pm}$ and K_S
  - $B^0 \to D^{*+}(\to D^0\pi^+)\ell^-\nu$ has peculiar kinematics
    - π^+ almost at rest w.r.t. D^{*+}
      ➔ D^{*+} momentum can be estimated from π^+ alone
    - Calculate $m_\nu^2 = (p_B - p_{D^*} - p_\ell)^2$ for all π^+

    ➔ Reject events consistent with $m_\nu = 0$
- Vetoed events are depleted in $b \to u\ell\nu$
  - Use them to validate simulation of background distributions
- We've got (m_X, q^2) distribution of a signal-enriched sample

Fitting m_X



- BABAR data, 80 fb^{-1} on resonance
  - Simple fit in m_X shows clear $b \to u\ell\nu$ signal
- Inclusive BF measured to be

$$\mathcal{B}(B \to X_u l\nu) = (2.81 \pm 0.32_{\text{stat}} \pm 0.31_{\text{sys}}{}^{+0.23}_{-0.21}{}_{\text{theo}}) \times 10^{-3}$$

$$|V_{ub}| = (5.22 \pm 0.30_{\text{stat}} \pm 0.31_{\text{syst}} \pm 0.43_{\text{theo}}) \times 10^{-3}$$

Fitting m_X vs. q^2

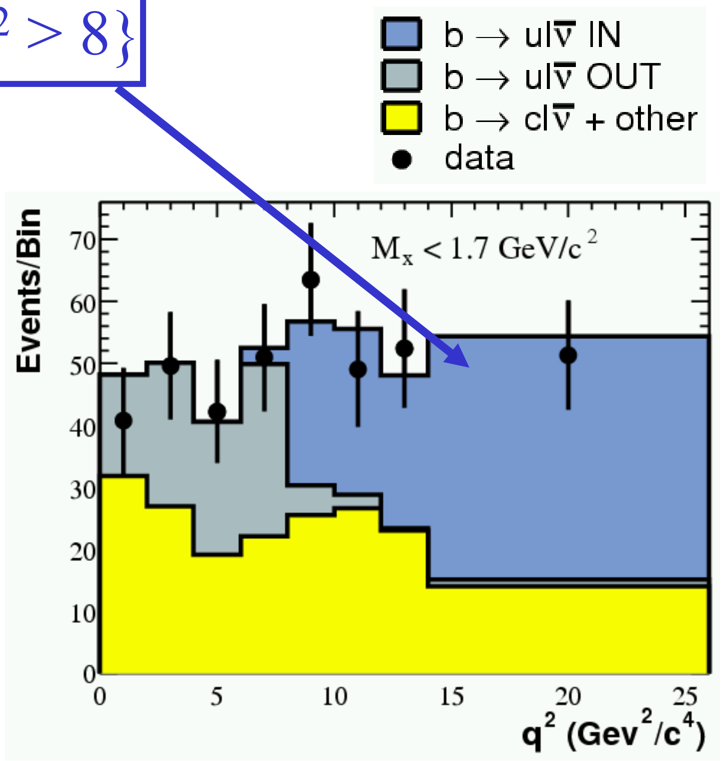
- 2-D fit to measure $\Delta\mathcal{B}$ in $\boxed{\{m_X < 1.7,\ q^2 > 8\}}$
  - Good resolution allows clean extraction of $\Delta\mathcal{B}$

$$\Delta\mathcal{B} = (0.90 \pm 0.14_{\text{stat}} \pm 0.14_{\text{syst}}\,{}^{+0.01}_{-0.02}{}_{\text{theo}}) \times 10^{-3}$$

- Signal event fraction into the "box" calculated by Bauer *et al.*
  - hep-ph/0111387

$$|V_{ub}| = \sqrt{\frac{192\pi^3}{\tau_B G_F^2 m_b^5} \frac{\Delta\mathcal{B}}{G}} \qquad \boxed{G = 0.282 \pm 0.053}$$

$$= (4.98 \pm 0.40_{\text{stat}} \pm 0.39_{\text{syst}} \pm 0.47_{\text{theo}}) \times 10^{-3}$$



Inclusive $|V_{ub}|$ Results

BABAR hep-ex/0408075

BABAR hep-ex/0408045

BABAR hep-ex/0408068

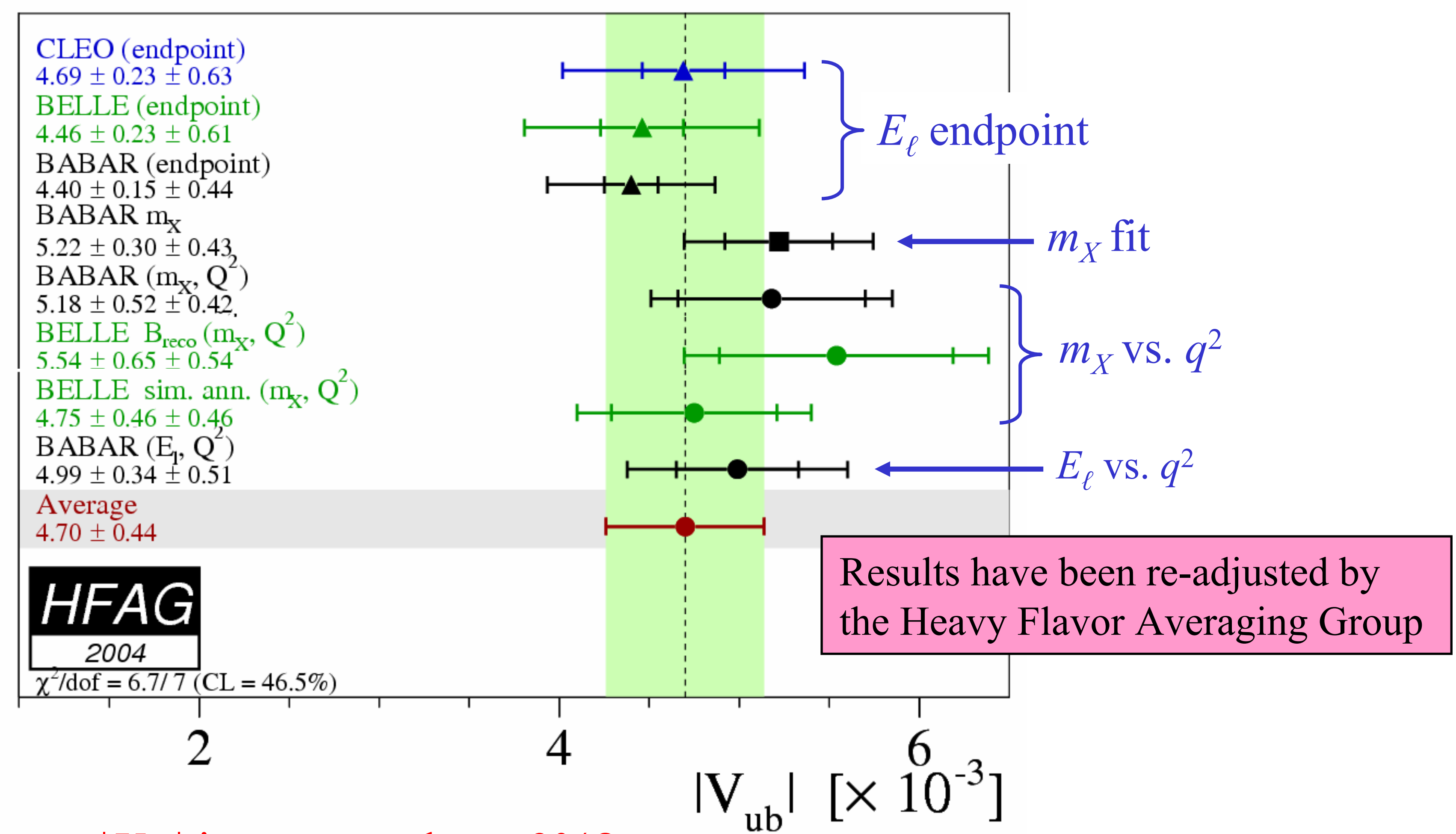
- Summary of BABAR $|V_{ub}|$ results

Technique	$\lvert V_{ub}\rvert \times 10^3$	$\Delta(\mathrm{SF}) \times 10^3$
$E_\ell > 2.0$ GeV	$4.40 \pm 0.13_{\mathrm{stat}} \pm 0.25_{\mathrm{sys}} \pm 0.38_{\mathrm{theo}}$	0.46
E_ℓ vs. q^2	$4.99 \pm 0.23_{\mathrm{stat}} \pm 0.42_{\mathrm{sys}} \pm 0.32_{\mathrm{theo}}$	0.42
$m_X < 1.55$ GeV	$5.22 \pm 0.30_{\mathrm{stat}} \pm 0.31_{\mathrm{sys}} \pm 0.43_{\mathrm{theo}}$	0.45
m_X vs. q^2	$4.98 \pm 0.40_{\mathrm{stat}} \pm 0.39_{\mathrm{sys}} \pm 0.47_{\mathrm{theo}}$	0.06

- Statistical correlation between the m_X and m_X-q^2 results is 72%. Others negligible
- Theoretical error of the m_X-q^2 result is different from the rest ➔ Negligible SF dependence

How much $|V_{ub}|$ moves if the SF is determined by the CLEO data

Inclusive $|V_{ub}|$ in Perspective



- $|V_{ub}|$ is measured to ±9%?

Caveats + Outlook

- Improved precision of $|V_{ub}|$ require re-evaluation of theoretical uncertainties
  - Poor convergence of OPE calculation in the small m_X region
    - Improved calculations using SCET available now
  - NLO($1/m_b$) non-perturbative corrections differ between $b \to u\ell\nu$ and $b \to s\gamma$
    - Quantitative estimates in literature more-or-less agree
  - Weak annihilation diagrams may have large (20%?) effect near the lepton energy endpoint
    - Difference between B^0 and B^+ needs to be measured
- Theory and experiment join forces to push the limit

Exclusive $|V_{cb}|$

- $B \to D^* \ell \nu$ decay rate is given by

$$\frac{d\Gamma(B \to D^* l \nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \mathcal{F}(w)^2 \mathcal{G}(w)$$

form factor

phase space

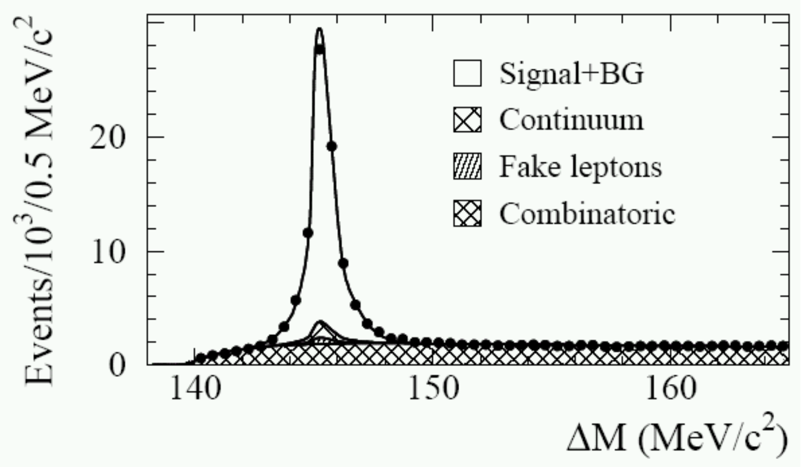
D^* boost γ in the B rest frame

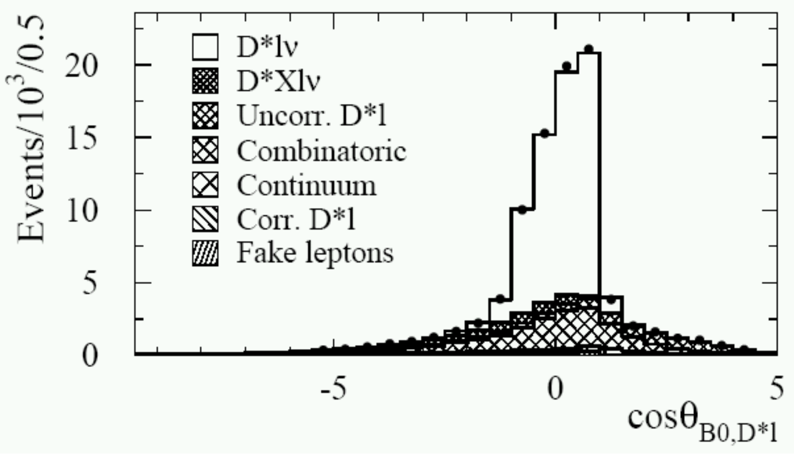
  - $\mathcal{F}(w)$ is calculable at $w = 1$, i.e. zero-recoil
    - $\mathcal{F}(1) = 1$ at the heavy-quark limit ($m_b = m_c = \infty$)
    - Lattice calculation gives $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$ Hashimoto et al, PRD 66 (2002) 014503
  - Shape of $\mathcal{F}(w)$ unknown
    - Parameterized with ρ^2 (slope at $w = 1$) and R_1, R_2
    - Use R_1 and R_2 determined by CLEO, PRL 76 (1996) 3898
- Measure $d\Gamma/dw$ to fit $\mathcal{F}(1)|V_{cb}|$ and ρ^2

$B \to D^* \ell \nu$ Sample

- BABAR data, 80 fb^{-1} on Υ(4*S*)
- Find events with D^{*+} + lepton
  - $D^{*+} \to D^0 \pi^+$ with $D^0 \to K^- \pi^+, K^- \pi^+ \pi^- \pi^+, K^- \pi^+ \pi^0$
  - $1.2 < p_\ell < 2.4$ GeV/c
- Background
  - Fake D^*
    - $D^* - D$ mass difference
  - True D^* but not $B \to D^* \ell \nu$

$$\cos\theta_{BY} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2 p_B p_{D^*\ell}}$$





Determination of $F(1)|V_{cb}|$

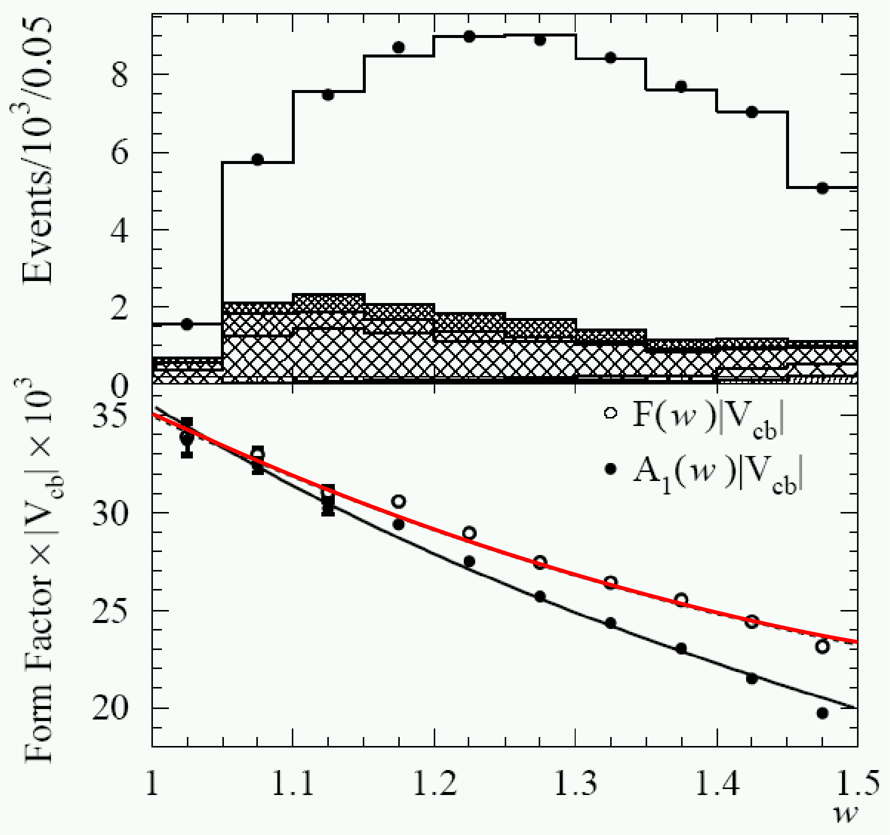
- Correct for efficiency → *w* distribution
  - Slow pion (from D^* decays) efficiency depend on *w*

- Fitting *dN/dw*, we find

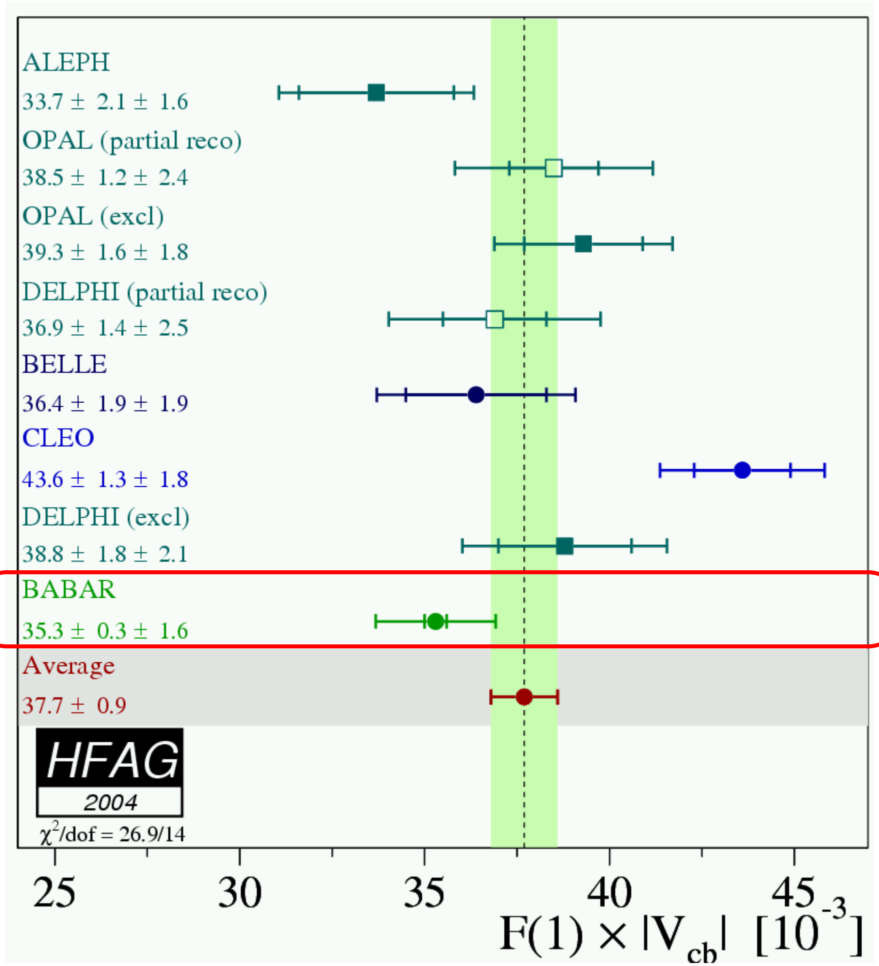
$$\mathcal{F}(1)\left|V_{cb}\right| = (34.03 \pm 0.24_{\text{stat}} \pm 1.31_{\text{syst}}) \times 10^{-3}$$

$$\rho^2 = 1.23 \pm 0.02_{\text{stat}} \pm 0.28_{\text{syst}}$$

$$\mathcal{B}_{D^*\ell\nu} = (4.68 \pm 0.03_{\text{stat}} \pm 0.29_{\text{syst}})\%$$



Determination of $|V_{cb}|$



- BaBar result compares well with existing measurements
  - ← Results have been adjusted to use common inputs
- Using $\mathcal{F}(1) = 0.91 \pm 0.04$, the world average is

$$|V_{cb}| = (41.4 \pm 1.0_{\text{expt}} \pm 1.8_{\text{theo}}) \times 10^{-3}$$

  - Agrees with the inclusive measurement
  - Accuracy ±5%

Exclusive $|V_{ub}|$

- Measure specific final states, e.g., $B \to \pi\ell\nu$
  - Good signal-to-background ratio
  - Branching fraction in $\mathcal{O}(10^{-4})$ → Statistics limited
- So far $B \to \pi\ell\nu$ and $\rho\ell\nu$ have been measured
  - Also seen: $\mathcal{B}(B \to \omega\ell\nu) = (1.3 \pm 0.5) \times 10^{-4}$ [Belle hep-ex/0402023]

    $\mathcal{B}(B \to \eta\ell\nu) = (0.84 \pm 0.36) \times 10^{-4}$ [CLEO PRD68:072003]
- Need Form Factors to extract $|V_{ub}|$
  - e.g. $$\frac{d\Gamma(B \to \pi\ell\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 \left|f_+(q^2)\right|^2$$
  - How are they calculated?

Form Factors

- Form Factors are calculated using:
  - Lattice QCD ($q^2 > 16$ GeV^2)
    - Existing calculations are "quenched" ➔ ~15% uncertainty
  - Light Cone Sum Rules ($q^2 < 16$ GeV^2)
    - Assumes local quark-hadron duality ➔ ~10% uncertainty
- All of them have uncontrolled uncertainties
  - LQCD and LCSR valid in different q^2 ranges ➔ No crosscheck
- Unquenched LQCD starts to appear
  - Preliminary $B \to \pi\ell\nu$ FF from FNAL+MILC (hep-lat/0409116), HPQCD (hep-lat/0408019)
  - Current technique cannot do $B \to \rho\ell\nu$

Measurements

- Concentrate on $B \to \pi \ell \nu$

	B Sample	$\mathcal{B}(B \to \pi \ell \nu) \times 10^4$	q^2 bins	Reference
BABAR	Recoil of $B \to$ hadrons	$1.08 \pm 0.28_{\text{stat}} \pm 0.16_{\text{sys}}$	1	hep-ex/0408068
	Recoil of $B \to D^* \ell \nu$	$1.46 \pm 0.27_{\text{stat}} \pm 0.35_{\text{sys}}$	3	[ICHEP 2004]
Belle	Recoil of $B \to D^{(*)} \ell \nu$	$1.76 \pm 0.28_{\text{stat}} \pm 0.20_{\text{sys}}$	3	hep-ex/0408145
CLEO	Untagged	$1.33 \pm 0.18_{\text{stat}} \pm 0.13_{\text{sys}}$	3	PR D68,072003

  - Total rate is measured to ~12% accuracy
  - Need measurement in bins of q^2
    - LQCD calculation of FF available above 16 GeV^2
    - Small rate → Large statistical errors
- New measurements + unquenched LQCD calculations will make $|V_{ub}|$ extraction possible

Summary

- Semileptonic decays provide excellent probes for the weak and strong physics of the B mesons
  - $|V_{cb}|$ and $|V_{ub}|$ ➔ Complementary to $\sin 2\beta$ from CP violation
  - Heavy quark masses and the non-perturbative parameters

- $|V_{cb}|$ has been determined to ±2%
  - OPE fit of E_ℓ and m_X moments by BABAR gives

    $$|V_{cb}| = (41.4 \pm 0.4_{\mathrm{exp}} \pm 0.4_{\mathrm{HQE}} \pm 0.6_{\mathrm{th}}) \times 10^{-3}$$

    - Fit quality and consistency support validity of the OPE application
  - Exclusive $B \to D^* \ell \nu$ measurements agree

    $$|V_{cb}| = (41.4 \pm 1.0_{\mathrm{expt}} \pm 1.8_{\mathrm{theo}}) \times 10^{-3}$$ World average by HFAG

Summary

- Significant progress in determination of $|V_{ub}|$
  - Four (!) BABAR measurements of $|V_{ub}|$ with inclusive $b \to u\ell\nu$

Technique	$\lvert V_{ub}\rvert \times 10^3$
$E_\ell > 2.0$ GeV	$4.40 \pm 0.13_{\mathrm{stat}} \pm 0.25_{\mathrm{sys}} \pm 0.38_{\mathrm{theo}}$
E_ℓ vs. q^2	$4.99 \pm 0.23_{\mathrm{stat}} \pm 0.42_{\mathrm{sys}} \pm 0.32_{\mathrm{theo}}$
$m_X < 1.55$ GeV	$5.22 \pm 0.30_{\mathrm{stat}} \pm 0.31_{\mathrm{sys}} \pm 0.43_{\mathrm{theo}}$
m_X vs. q^2	$4.98 \pm 0.40_{\mathrm{stat}} \pm 0.39_{\mathrm{sys}} \pm 0.47_{\mathrm{theo}}$

    - Overall accuracy of $|V_{ub}|$ around 10%
  - New measurements of $B \to \pi\ell\nu$ + unquenched LQCD calculations will measure $|V_{ub}|$ soon